

*THE EFFECT OF REINFORCER DELAYS ON THE FORM OF THE  
FORGETTING FUNCTION*

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Pigeons were trained in a matching-to-sample procedure with retention intervals of 0, 2, 4, 6, and 8 s mixed within each session. In different conditions, reinforcement was delayed by 0, 1, 2, 4, 6, or 8 s from correct choice responses. Discriminability decreased with increasing retention-interval duration and with increasing reinforcer delay. Exponential forgetting functions were fitted to discriminability measures plotted as a function of retention interval. Initial discriminability (intercept of the fitted functions) decreased with increasing reinforcer delay. Rate of forgetting (slope of the fitted functions) increased with reinforcer delay, suggesting an interaction between the effects of reinforcer delay and retention interval. The data were well described by multiplying an exponential function describing the effects of retention interval by a hyperbolic function describing the effect of reinforcer delay. This description included an interaction term that allowed for a greater effect of reinforcer delay at longer retention intervals.

*Key words:* forgetting functions, reinforcer delay, retention interval, delayed matching-to-sample, pigeon

In delayed matching-to-sample (DMTS) tasks, choices of the comparison stimulus that match a previously presented sample stimulus are reinforced. The typical result is a monotonically decreasing forgetting function. Such functions show that as the delay or retention interval between the sample and comparison stimuli presentations is increased, the accuracy of an animal's choice of the matching comparison decreases (White, 1985, 2001; White & Wixted, 1999, 2001; Wixted, 1989). Here, we use *retention interval* to refer to the temporal distance between sample and comparison stimuli and *forgetting* to refer to reduced discriminability at longer retention intervals compared to short intervals.

Measures of discriminability across increasing retention interval in DMTS tasks are well fit by curvilinear functions with two free parameters; intercept or initial discriminability at time zero, and slope or rate of forgetting. One such monotonically decreasing function is the negative exponential function

$$y = ae^{-bt}, \quad (1)$$

where  $t$  is retention-interval duration,  $a$  is the intercept, and  $b$  is the slope. This function has been found to fit data from DMTS studies with nonhuman animals (Rubin & Wenzel, 1996; White, 1985), although other functions fit just as well (McCarthy & White, 1987; Wixted & Ebbesen, 1991).

The intercept and slope of the exponential function are independently influenced by different aspects of the DMTS procedure (White, 1991). In general, the intercept is affected by aspects of the sample stimulus (White, 1985; White & McKenzie, 1982). For example, increasing the response requirement to the sample stimulus (Roberts, 1972; White, 1985), increasing sample stimulus disparity (White, 1985), and increasing sample duration (Foster, Temple, MacKenzie, DeMello, & Poling, 1995) all increase initial discriminability ( $a$ ) without affecting rate of forgetting ( $b$ ). Rate of forgetting is affected by events during the retention interval (White, 1985). For example, retroactive interference from turning on the houselight during the retention interval increases the rate of forgetting without changing the intercept (Harper & White, 1997), as does proactive interference from the previous trial (Edhouse & White, 1988).

How do the consequences of remembering affect the intercept and slope of forgetting functions? Nevin and Grosch (1990) signaled

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whether the reinforcer on a trial within a session would be large or small. The intercept of the fitted exponential functions for large reinforcer trials was higher than for small reinforcer trials, but the rate of forgetting was the same for both trial types. This conclusion was confirmed in similar studies by Jones, White, and Alsop (1995) and by McCarthy and Voss (1995).

D'Amato and Cox (1976) suggested that delaying a reinforcer reduces its value in the same way as decreasing the magnitude of a reinforcer. Studies with nonhuman animals have supported this idea by showing that delaying the delivery of reinforcers results in slower acquisition of tasks (Renner, 1964), slower rates of responding (Chung, 1965; Chung & Herrnstein, 1967), and less accurate performance on discrimination tasks (D'Amato & Cox). The results of a range of studies with choice procedures summarized by Mazur (2001) support the assumption that the effect of a reinforcer on behavior decreases as a hyperbolic function of reinforcer delay ( $D$ ). That is,

$$y = \frac{g}{1 + hD}, \quad (2)$$

where  $g$  is the intercept and  $h$  is the half-life (or slope) of the hyperbolic function.

In a delayed symbolic matching-to-sample task, McCarthy and Davison (1986, 1991) included delays either between the sample and comparison stimulus presentations (retention interval) or between the choice response and the reinforcer delivery (reinforcer delay). In their studies, discriminability decreased as the delay to reinforcement was lengthened, and to a greater extent when the retention interval was increased. In both studies, they held one delay type constant at 0 s while varying the other. When the retention interval was held constant at 0 s, discriminability decreased as a hyperbolic function of reinforcer delay, consistent with Equation 2. It was not possible, however, to determine the effect of delayed reinforcement on the form of the forgetting function because reinforcer delays were not combined with retention intervals of longer than 0 s. Panels a and b of Figure 1 show a reanalysis of McCarthy and Davison's (1986, 1991) data. A complete forgetting function, with retention interval on the

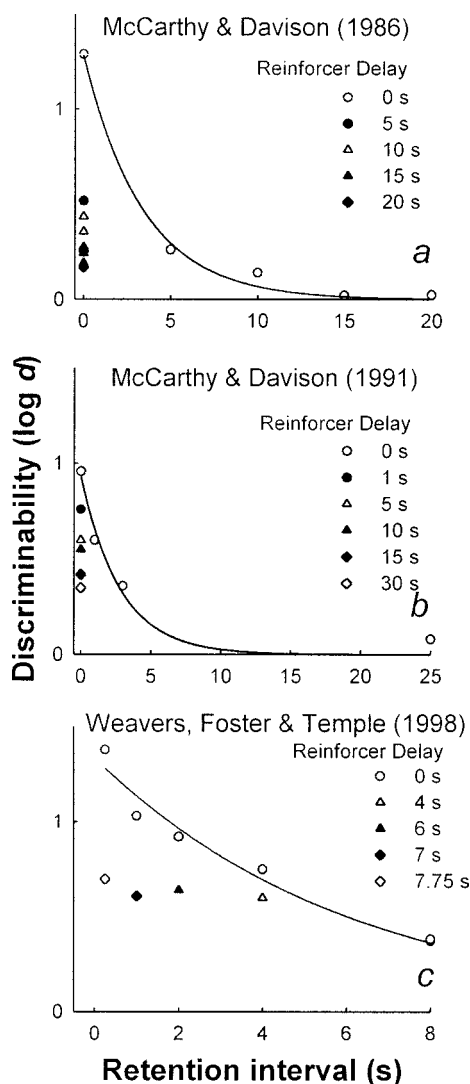


Fig. 1. a. Reanalysis of McCarthy and Davison (1986) showing discriminability ( $\log d$ ) at each retention interval for reinforcer delays of 0, 5, 10, 15, and 20 s. b. Reanalysis of McCarthy and Davison (1991) showing discriminability ( $\log d$ ) at each retention interval for reinforcer delays of 0, 1, 5, 10, 15, and 30 s. c. Discriminability ( $\log d$ ) of the pigeons' responses at each retention interval for reinforcer delays of 0, 4, 6, 7, and 7.75 s in Weavers et al.'s (1998) study. In each case, lines were fitted to the 0-s reinforcer delay data only.

horizontal axis, was only available when the reinforcer delay was 0 s.

Weavers, Foster, and Temple (1998) measured accuracy using a combination of retention intervals and reinforcer delays by fixing the sample to reinforcer delay at 8 s on trials where the retention interval was 0.25, 1, 2, 4,

or 8 s. This meant, for example, that if the retention interval was 8 s, reinforcement occurred immediately after the choice response, but if the retention interval was 1 s, reinforcement was delayed for an additional 7 s after the pigeon had completed the sample stimulus response requirement. Weavers et al. found that reinforcer delays decreased matching accuracy. Although matching accuracy was measured at a larger range of retention intervals and reinforcer delays than in the McCarthy and Davison (1986, 1991) studies, there were not enough data collected to plot forgetting functions with constant reinforcer delays.

Figure 1 shows the matching accuracy of hens in Weavers et al.'s (1998) study at each retention interval. The standard forgetting function with immediate reinforcement (0-s reinforcer delay) is shown as a smooth curve fitted to the open circles where accuracy decreases with increasing retention interval. Weavers et al. measured accuracy at a combination of different reinforcer delays and different retention intervals. They did not, however, vary retention interval for the different values of reinforcer. It is not possible, therefore, to determine the effects of reinforcer delays on the forgetting function on the basis of the data reported by Weavers et al.

Wilkie and Spetch (1978) investigated the effect of reinforcer delays on DMTS accuracy by first introducing a fixed-ratio (FR) response requirement to the comparison stimuli and then substituting a delay for the FR requirement. They found that both increasing the FR from 1 to 16 and increasing the reinforcer delay from 0 to 9 s caused a decrement in accuracy. It is difficult, however, to determine the effect of the manipulations on the form of the forgetting function from these data because only 0- and 5-s retention intervals were used, giving only two points on a forgetting function.

In summary, whereas the effect of reinforcer delay on remembering has been studied, no study has set out to determine the effect of reinforcer delay on the form of the forgetting function. Although it seems clear from studies reported by McCarthy and Davison (1986, 1991), Weavers et al. (1998), and Wilkie and Spetch (1978) that accuracy decreases with a delay between choice and re-

inforcement, it is not yet possible to draw a conclusion about the effects of reinforcer delay on the intercept and slope of the forgetting function.

The aim of the present experiment was to investigate the effect of reinforcer delay on the form of the forgetting function. A standard DMTS procedure was used, with retention intervals of 0, 2, 4, 6, and 8 s programmed to occur equally often in each daily session. The reinforcer delay was varied across conditions. Reinforcement, or a black-out period of equal duration following error responses, was delivered either immediately or after 1, 2, 4, 6, or 8 s after the choice response in different conditions. Forgetting functions plotting discriminability as a function of the retention interval for each reinforcer delay were expected to show a decrease in accuracy as the reinforcer delay increased. The question was whether reinforcer delay would influence the intercept or the slope of the forgetting function.

## METHOD

### *Subjects*

Eight homing pigeons aged between 1 and 5 years and numbered T1 through T4 and P1 through P4 were individually housed in wire cages measuring 400 mm deep, 500 mm high, and 400 mm wide where they had free access to water and grit. The pigeons were weighed daily and maintained at  $85\% \pm 10\%$  g of their free-feeding weights through postexperimental feeding of a mixture of wheat, corn, peas, and pellets. If a pigeon's weight fell outside the range, it was excluded from experimental sessions until its weight was within the range.

### *Apparatus*

Two custom-built experimental chambers were used. The chambers were constructed from particle-board painted black and had internal dimensions of 285 mm high, 320 mm wide, and 500 mm deep. Three translucent plastic response keys, 30 mm in diameter, were located flush on one wall of each chamber 200 mm from the grid floor and 75 mm apart. The keys could be illuminated red or green and required a force of at least 0.15 N to be operated. A hopper situated behind an aperture 85 mm below the center key provid-

Table 1  
Order of conditions and the number of sessions completed for each pigeon.

Conditions	Reinforcer delay (s)	T1	T2	T3	T4	Reinforcer delay (s)	P1	P2	P3	P4
1	0	30	30	22	25	0	27	31	30	20
2	2	22	22	20	20	8	24	24	24	21
3	4	25	25	25	21	6	25	25	25	23
4	6	21	21	21	20	4	21	21	21	20
5	8	26	26	26	25	2	26	26	25	24
6	0	78	78	75	70	0	78	78	76	64
7	1	26	27	25	23	2	27	26	27	21
8	2	35	38	29	30	1	37	41	31	23
9	0	29	25	25	21	0	28	30	27	18
10	1	37	34	30	32	2	38	38	34	22
11	2	32	28	21	22	1	25	34	21	23
12	0	28	28	20	21	0	25	28	27	20
13	2	25	26	22	20	8	23	23	23	21
14	4	28	25	25	26	6	20	20	20	20
15	6	20	29	26	25	4	26	26	26	20
16	8	20	20	20	20	2	36	35	35	21

ed access to wheat when raised. A light inside the aperture was illuminated when the hopper was raised.

#### *Procedure*

All pigeons had previously served in standard DMTS experiments (Sargisson & White, 2001) and so did not require any initial training. Experimental sessions were conducted 7 days per week. Each session was terminated after 50 min had elapsed, or after 90 trials had been completed, whichever occurred sooner. The first 10 trials of each session were used as warm-up trials and data from these trials were not included in any analyses.

Trials began with the center key lit either red or green (the sample stimulus). Five responses to the center key turned the center key light off and initiated the retention interval (0, 2, 4, 6, or 8 s). After the retention interval, one of the side keys was lit red and the other green (the comparison stimuli). Over the last 80 trials in each session, there were equal numbers of red and green sample stimuli combined with red and green comparison stimuli on the left and right keys. The five delays occurred in the same quasi-random order in each session equally often with each combination of sample stimulus and comparison stimulus location. The order of trials was arranged so that if the session ended prior to all 80 trials being completed, approximately equal numbers of trials with each delay had occurred. Appendix A contains the

actual numbers of trials completed by each pigeon in the last five sessions of each condition. A peck to the red key following presentation of the red sample was correct, and a peck to the green key following presentation of the green sample was correct. Each correct response was followed by 3-s access to wheat. Incorrect responses produced a 3-s blackout. Each trial was followed by a 12-s intertrial interval during which all keys and the chamber were dark and responses were ineffective.

All experimental conditions used retention intervals of 0, 2, 4, 6, or 8 s, but in each condition there were different reinforcer delays. There were 16 conditions. Condition 1 for all pigeons was the baseline condition where correct responses at each retention interval were immediately followed by reinforcement. In subsequent conditions, correct responses were reinforced 1, 2, 4, 6, or 8 s after the choice response was made. Reinforcer delay conditions were replicated as shown in Table 1. The order of experimental conditions for Pigeons T1, T2, T3, and T4 was different from the order of conditions for Pigeons P1, P2, P3, and P4 (Table 1). Each condition was conducted for all pigeons until each pigeon had been trained for a minimum of 20 sessions. Conditions were changed for all 8 pigeons at the same time. There were two exceptions to this rule. The first replication of the 0-s reinforcer delay condition was in effect for over 64 sessions to assure reinstate-

ment of steady-state baseline performance. Conditions 5, 8, and 10 were in effect for a minimum of 24, 23, and 22 sessions, respectively, owing to a variation in laboratory organization. Table 1 shows the order of the conditions and the number of sessions completed by each pigeon in each condition.

## RESULTS

Totals of choice responses to red and green sample stimuli for the last 5 days of each condition for individual pigeons (Appendix A) were transformed into  $\log d$  measures of discriminability using  $\log d = 0.5 \log [(CR/ER)(CG/EG)]$  where  $CR$ ,  $ER$ ,  $CG$ , and  $EG$  are the numbers of correct (C) and incorrect (E) red and green choices, respectively.  $\log d$  is a bias-free measure of discriminability described by Davison and Tustin (1978). It is the same as the measure of discriminability from Luce's (1963) choice theory, except that  $\log d$  has the base 10. The data from Pigeon T1 were omitted from the analyses, as this pigeon did not respond in every condition. The  $\log d$  values for each retention interval were averaged over replications of each reinforcer delay for each pigeon. This averaging was justified by a statistically nonsignificant effect of replications in an analysis of variance for repeated measures on the factors of retention interval and replications of reinforcer-delay conditions.

Exponential functions (Equation 1) were fit to the  $\log d$  values from the response totals from the last five sessions in each reinforcer delay condition using the nonlinear least squares procedure provided by Sigmaplot® (Marquardt, 1963). The results of these fits are shown in Table 2, which gives the values of intercept and slope and variance accounted for by the best fitting exponential functions for individual pigeons. Fits were generally satisfactory as indicated by the variance in the data accounted for by the fitted functions that averaged 87.3%. (Note, however, that flatter functions are necessarily associated with smaller values of variance accounted for.) Other functions, including exponential in the square root of time, hyperbola, and power functions, were also fitted to the data but none had a clear advantage over the exponential.

The results for individual pigeons (Table 2

and Appendix A) are summarized in Figure 2 (left panel) where the mean discriminability values averaged over pigeons are plotted as a function of retention interval duration, with reinforcer delay as the parameter. As reinforcer delay increased, the intercepts of the fitted exponential functions decreased. The parameter values in Figure 2 indicate that slope increased as a function of increasing reinforcer delay.

Figure 3 (left panels) shows the values of the intercept parameter ( $a$ ) for the forgetting functions for individual pigeons. The mean intercept of the functions (Figure 3, bottom panel left) decreased with increasing reinforcer delay. This conclusion was confirmed by a nonparametric trend analysis ( $z = -5.43$ ,  $p < .01$ ; Ferguson, 1965, p. 367).

Figure 3 (right panels) also shows the values for the slope parameters ( $b$ ) for individual pigeons. Figure 3 (bottom panel right) shows that the mean slope for the forgetting functions increased with increasing reinforcer delay. This effect was small, but it was statistically significant according to a nonparametric trend analysis ( $z = 2.79$ ,  $p < .01$ ).

The present analyses were based on the last five sessions for each condition, although the criterion for changing sessions resulted in different numbers of sessions completed per condition by different pigeons. In order to test whether continued training for some pigeons in some conditions altered the results, an additional analysis of discriminability measures based on the five sessions prior to the last five sessions in each condition was conducted for all pigeons. Figure 3 shows the intercept and slope parameters for the functions fitted to  $\log d$  measures based on data for the last five sessions and the preceding five sessions. There was little difference in the parameter values obtained from these two blocks of sessions, showing that the data were stable.

The right panel of Figure 2 shows the same data as in the left panel, but plotted a different way; that is, mean discriminability plotted as a function of reinforcer delay at each retention interval. Hyperbolic functions (Equation 2) are shown fitted to these mean discriminability values. Table 2 gives the values of intercept, slope, and variance accounted for by Equation 2 for each pigeon. Figure 2 and Table 2 indicate that the effect of rein-



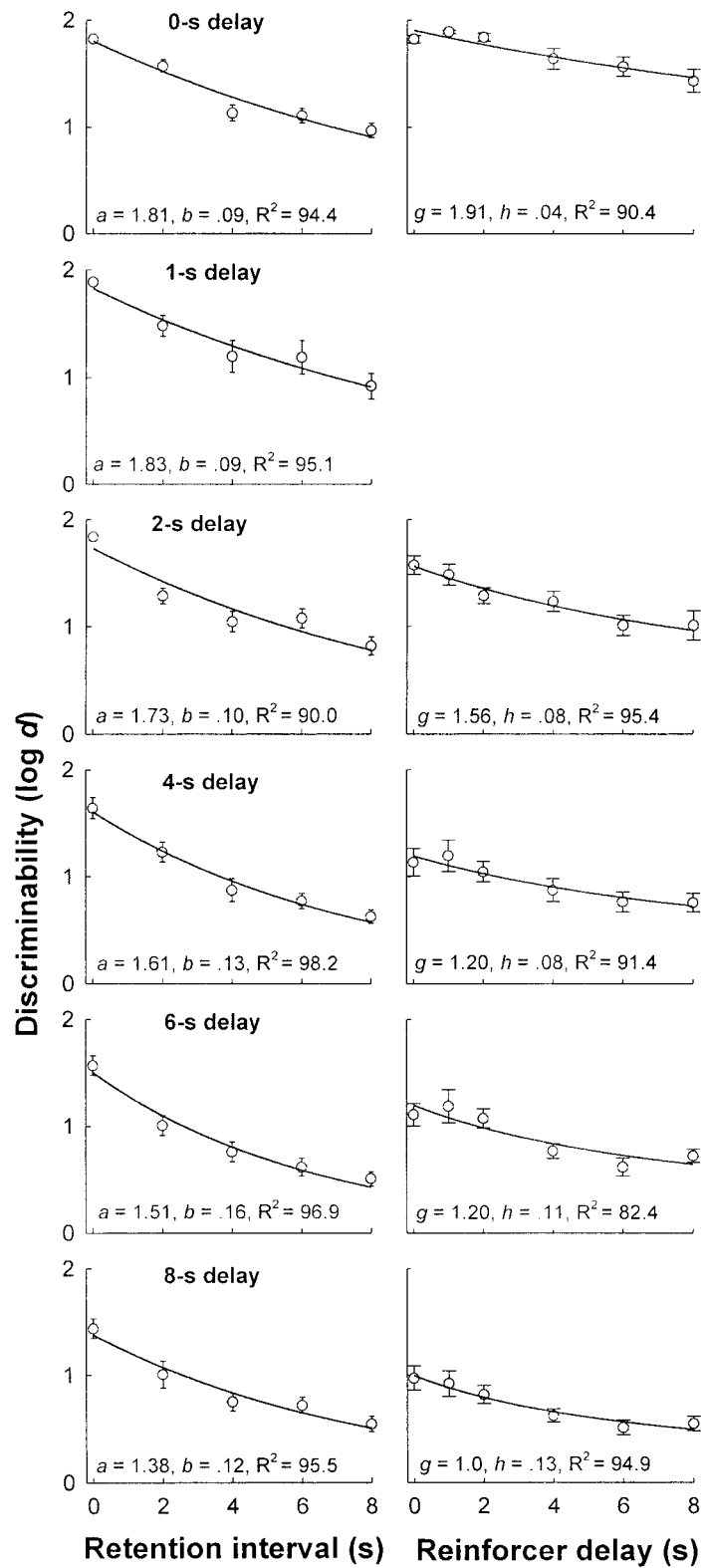
Table 2

Variance accounted for ( $R^2$ ), intercept and slope parameters obtained for exponential functions plotted as a function of retention interval (left panel), and hyperbolic functions plotted as a function of reinforcer delay (right panel).

Pigeon	Exponential retention interval				Hyperbolic reinforcer delay			
	Delay	VAC ( $R^2$ )	$a$	$b$	Delay (s)	VAC ( $R^2$ )	$g$	$h$
T2	0	74.7	1.58	.08	0	68.9	1.8	.05
	1	98.6	1.77	.13				
	2	79.8	1.68	.13	2	67.0	1.3	.10
	4	94.0	1.50	.11	4	84.5	1.0	.11
	6	93.2	1.14	.18	6	50.3	0.9	.08
T3	8	66.1	1.24	.14	8	77.5	0.9	.14
	0	93.5	2.00	.06	0	93.6	1.9	.00
	1	88.2	2.02	.07				
	2	92.6	1.95	.08	2	45.1	1.8	.02
	4	97.0	1.97	.09	4	82.2	1.6	.06
T4	6	96.6	1.85	.13	6	84.5	1.4	.10
	8	94.4	1.94	.14	8	87.1	1.0	.06
	0	92.2	1.66	.08	0	67.6	1.9	.06
	1	80.0	1.77	.12				
	2	84.2	1.75	.14	2	78.9	1.3	.05
P1	4	94.9	1.63	.15	4	63.9	0.9	.06
	6	96.4	1.43	.14	6	88.0	1.0	.09
	8	90.7	1.05	.11	8	97.8	0.9	.17
	0	94.2	1.89	.04	0	90.0	1.9	.04
	1	31.7	1.86	.02				
P2	2	30.7	1.53	.03	2	87.3	1.7	.09
	4	99.5	1.72	.13	4	67.2	1.7	.14
	6	96.7	1.49	.16	6	75.1	1.7	.19
	8	98.6	1.42	.10	8	84.5	1.6	.24
	0	78.6	1.90	.10	0	68.2	1.9	.01
P3	1	71.8	1.86	.06				
	2	96.9	1.87	.12	2	80.6	1.6	.06
	4	94.3	1.69	.14	4	8.1	1.0	.01
	6	92.8	1.76	.11	6	26.5	1.2	.06
	8	81.6	1.52	.08	8	35.5	0.9	.03
P4	0	89.5	1.79	.09	0	55.9	1.8	.03
	1	92.3	1.86	.11				
	2	74.3	1.74	.09	2	98.6	1.6	.14
	4	93.9	1.67	.19	4	85.0	1.1	.13
	6	92.6	1.37	.17	6	69.4	1.2	.12
P4	8	90.3	1.43	.19	8	81.6	0.9	.18
	0	96.2	1.88	.19	0	61.0	1.9	.07
	1	95.0	1.82	.17				
	2	96.8	1.66	.14	2	95.4	1.3	.11
	4	92.7	1.15	.12	4	52.3	0.8	.06
	6	94.6	1.53	.25	6	21.7	0.7	.05
	8	84.4	1.09	.14	8	38.3	0.5	.04

→

Fig. 2. Mean discriminability averaged across pigeons plotted as a function of retention interval with reinforcer delay as the parameter (left), and plotted again as a function of reinforcer delay with retention interval as the parameter (right). Error bars show the standard error of the mean across subjects. Exponential functions are shown fitted to the data points for the retention interval functions (left panel) and hyperbolic functions are fit to the reinforcer delay functions (right panel) with parameter values and percentage variance accounted for by each fit.



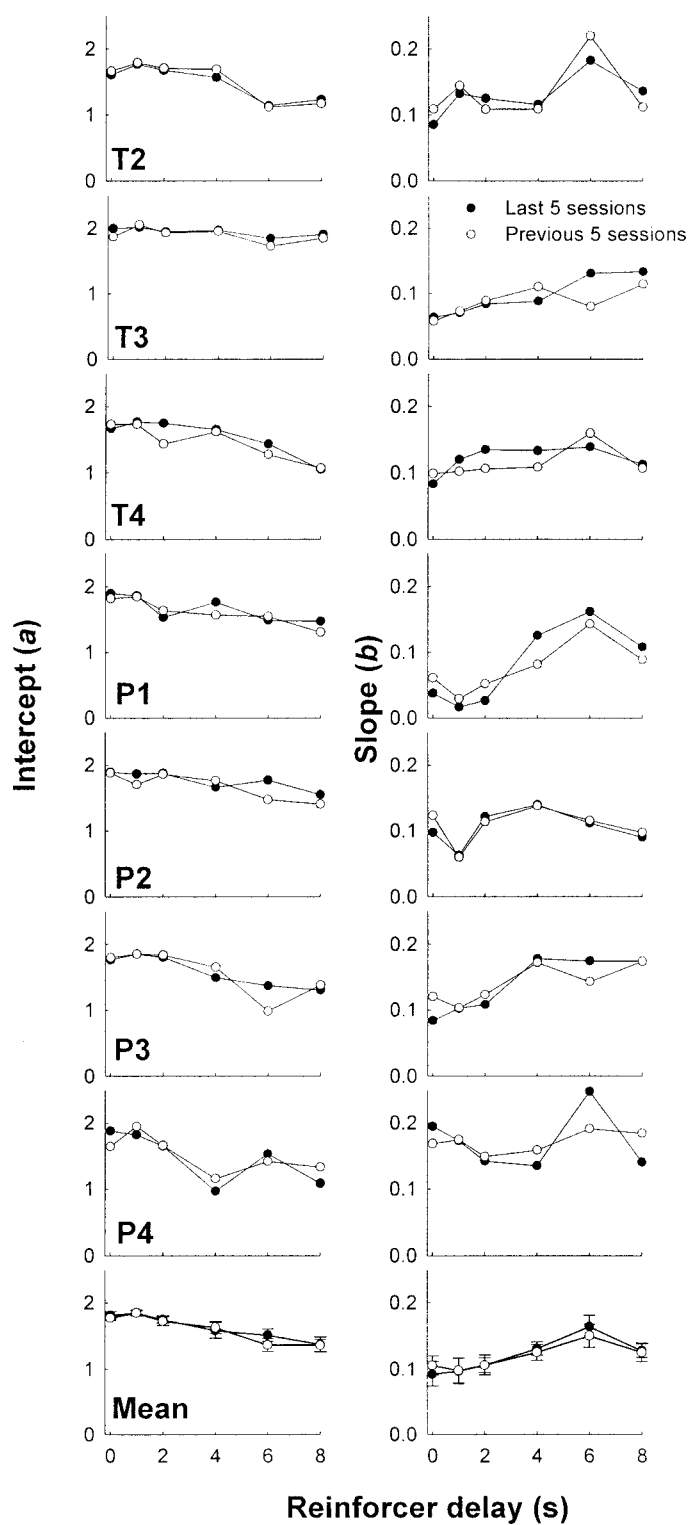


Fig. 3. Values of intercept (*a*) and slope (*b*) for exponential functions fitted to discriminability values ( $\log d$ ) from the last five sessions from the total number of sessions per condition (symbol) and from the five sessions prior to the last five sessions for each condition (symbol), for individual pigeons. The bottom panel shows intercept and slope values averaged across pigeons.



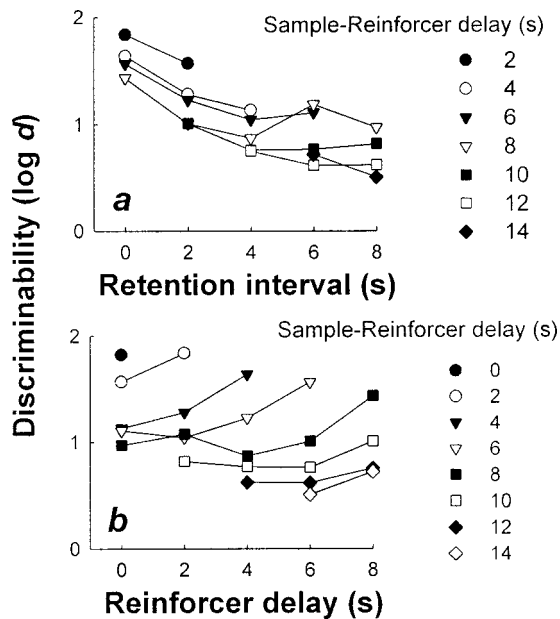


Fig. 4. a. Mean discriminability ( $\log d$ ) values across subjects as a function of retention interval at increasing sample-reinforcer delays. b. Mean discriminability as a function of reinforcer delay at increasing sample-reinforcer delays.

forcer delay was satisfactorily described by a hyperbolic function (Table 2). As retention interval increased, the intercepts of the reinforcer-delay functions decreased ( $z = 6.02$ ,  $p < .01$ ), and the slopes (half-life) increased ( $z = 2.41$ ,  $p < .05$ ).

Figure 2 indicates that discriminability decreased with retention-interval duration to a greater extent than with reinforcer delay. To compare the effect of retention interval and reinforcer delay on discriminability, exponential functions were fitted to discriminability plotted as a function of reinforcer delay. These functions (not shown) fitted just as well as the hyperbolic functions. Slopes of fitted exponential functions were greater for the retention-interval functions than for reinforcer-delay functions. This different effect of the two temporal variables was confirmed by analysis of variance,  $F(1, 6) = 17.88$ ,  $p < .01$ .

To assess the suggestion by Weavers et al. (1998) that the decrease in discriminability with increasing retention interval is due to the delay of reinforcement from the sample stimulus, Figure 4 plots the mean data from the present experiment for constant sample-

reinforcer delays (cf. Figure 1). Figure 4a shows mean discriminability ( $\log d$ ) as a function of retention interval at each sample-reinforcer delay. Figure 4b shows mean discriminability ( $\log d$ ) as a function of reinforcer delay at each sample-reinforcer delay. Figure 4a is comparable to the bottom panel of Figure 1 from Weavers et al.'s study. If discriminability is a function of the sample-reinforcer delay, lines connecting discriminability at each sample-reinforcer delay as a function of retention interval would be flat. The functions for the present data in Figure 4 are contrary to the notion that performance is determined by the time between the sample and the reinforcer. As a check, a further condition of 56 to 80 sessions was conducted using the present procedure, but with each retention interval paired with a reinforcer delay to maintain a constant 8-s sample to reinforcer delay as in Weavers et al. Discriminability at each retention interval from this single condition (Appendix B) was consistent with the functions from Figure 2 for each reinforcer delay.

## DISCUSSION

Increasing the reinforcer delay in a DMTS task decreased discriminability at all retention intervals. This change in accuracy was shown by the decrease in the intercept (initial discriminability) of exponential forgetting functions fitted to discriminability plotted as a function of retention interval, with increasing reinforcer delay. The decrease in initial discriminability when the reinforcer delay was increased was similar to that found when the magnitude of reinforcement is decreased (Jones, White, & Alsop, 1995; Nevin & Grosch, 1990). The difference between the present results and those found when reinforcer magnitude is varied is shown in the slope values that increased with increasing reinforcer delay in the present experiment (Figure 3). Altering the reinforcer magnitude decreased initial discriminability with no change in the rate of forgetting, whereas in the present experiment altering the reinforcer delay affected both initial discriminability and rate of forgetting.

The magnitude of the effect of increasing retention interval on discriminability was larger than the effect of reinforcer delay (Fig-

ure 2). That is, the two temporal variables were scaled differently on the dimension of time, as concluded by Williams (1998). Additionally, the two variables appeared to interact. That is, the forgetting functions differed in terms of both their intercepts and slopes. Assuming that the effect of retention interval and reinforcer delay can be satisfactorily described by exponential and hyperbolic functions, respectively, the combined effect of the two variables can be described by multiplying the two functions. That is, at a given retention interval  $t$ , discriminability  $\log d$  is predicted by Equation 1. This value for  $\log d$  then serves as the intercept for the hyperbolic function that describes a further reduction in  $\log d$  with increasing reinforcer delay.

The interaction between the two temporal variables, however, suggests that either the effect of retention interval is amplified by longer reinforcer delays, or the effect of reinforcer delay is amplified by longer retention intervals. Considering the latter possibility, reinforcer delay  $D$  in Equation 2 is effectively lengthened by longer retention intervals, that is,  $D' = D(1 + kt)$ , where  $k$  qualifies the effect of the retention interval  $t$  on  $D$ . A possible mechanism for such an effect follows from the result that the biasing effects of reinforcers are greater at longer retention intervals (White & Wixted, 1999; Wixted, 1989). For example, with equal probability of reinforcement for correct green and red choice responses but no discrimination between red and green sample stimuli (at long delays), red and green are chosen with equal probability and independently of the sample stimuli, thus producing near-zero discriminability. Equation 3 describes the way that  $\log d$ , given by the exponential (Equation 1), is reduced by lengthening the reinforcer delay, according to a hyperbola (Equation 2). The hyperbolic component in Equation 3, however, includes the interaction term in which  $D$  is amplified by retention interval  $t$ . Discriminability is, thus, described by

$$\log d = ae^{-bt}/(1 + hD[1 + kt]). \quad (3)$$

When  $D = 0$ , the forgetting function is described simply by the negative exponential function given by Equation 1. For a fixed value of  $D$ , the same function describes the decrease in discriminability with increasing

Table 3

Parameter values and percentage of variance accounted for by fits of Equation 3 to individual three-dimensional plots and the mean plot in Figure 5 of  $\log d$  at each combination of retention interval and reinforcer delay.

Pigeon	R <sup>2</sup>	$a$	$b$	$h$	$k$
T2	83.6	1.711	.089	.045	.393
T3	92.9	2.005	.062	.007	1.63
T4	87.9	1.810	.103	.053	.172
P1	83.7	1.860	.017	.037	.738
P2	81.0	1.907	.090	.024	.155
P3	89.3	1.843	.081	.034	.768
P4	90.3	1.901	.176	.085	-.045
Mean	95.0	1.845	.080	.036	.382

retention interval duration, but the intercept  $a$  is multiplied by the term  $(1 + hD[1 + kt])$  for each value of  $D$ . The values of the slope parameters,  $b$  and  $h$ , describe the different effects of retention interval and reinforcer delay in decreasing discriminability, and  $k$  is the interaction between the two temporal variables.

For each pigeon, Equation 3 was fitted to three-dimensional plots of  $\log d$  at each combination of retention interval and reinforcer delay. The variance accounted for and parameter values are shown in Table 3. The variance accounted for by these fits was generally high (81 to 93%). The positive values of  $k$  obtained for all pigeons, except P4, show that the effect of the reinforcer delay was amplified at longer retention intervals. For Pigeon P4, the value of  $k$  was negative, but close to zero. For this pigeon, the effect of reinforcer delay on  $\log d$  remained effectively constant with changes in retention intervals. Figure 5 shows Equation 3 fitted to the discriminability values averaged over pigeons and plotted as a function of both retention interval and reinforcer delay. The fitted surface in Figure 5 accounted for 95% of the variance in mean discriminability. Equation 3 is one of several possible ways of describing the interacting effects of retention interval and reinforcer delay. The high percentage of variance in the data that Equation 3 accounts for provides further support for the conclusion that the two temporal variables interacted in their effects on discriminability.

Davison and Nevin (1999) extended their theoretical account of detection to describe performance in delayed matching to sample.

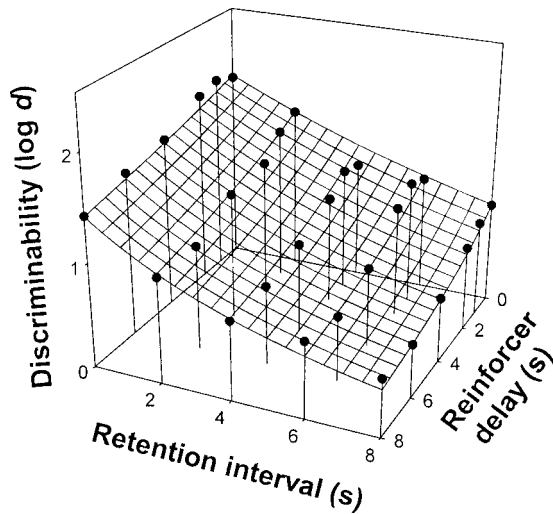


Fig. 5. Mean discriminability ( $\log d$ ) values across subjects as a function of both retention interval and reinforcer delay. The function was fit using Equation 3.

In their model, performance is influenced by discriminability between stimuli ( $d_s$ ) and discriminability between reinforcer contingencies, ( $d_r$ ). Choice between two alternatives following each sample stimulus is influenced by both the reinforcers arranged by the experimenter and by the generalized effects of those reinforcers as a result of less-than-perfect discriminabilities  $d_s$  and  $d_r$ . Increasing the delay from stimulus presentation results in the effective reinforcer probabilities in the signal detection matrix becoming more similar owing to a reduction in  $d_s$ , and more so as a result of a reduction in  $d_r$  with reinforcer delay. Predictions from their model are shown in Figure 6 (cf. Davison & Nevin, Figure 15). Because retention interval affects the successive discrimination between samples and hence  $d_s$ , and because reinforcer delay affects the concurrent discrimination between reinforcer contingencies and hence  $d_r$ , the model predicts an interaction between retention interval and reinforcer delay. Figure 6 (top panel) shows that theory predicts that reinforcer delay has a larger effect at short retention intervals than at long retention intervals. The interaction as described by Equation 3, and in the present data, however, is opposite to the interaction shown in Figure 6 (top panel). Figure 6 (center panel) summarizes this interaction by plotting discriminability values averaged over pigeons for re-

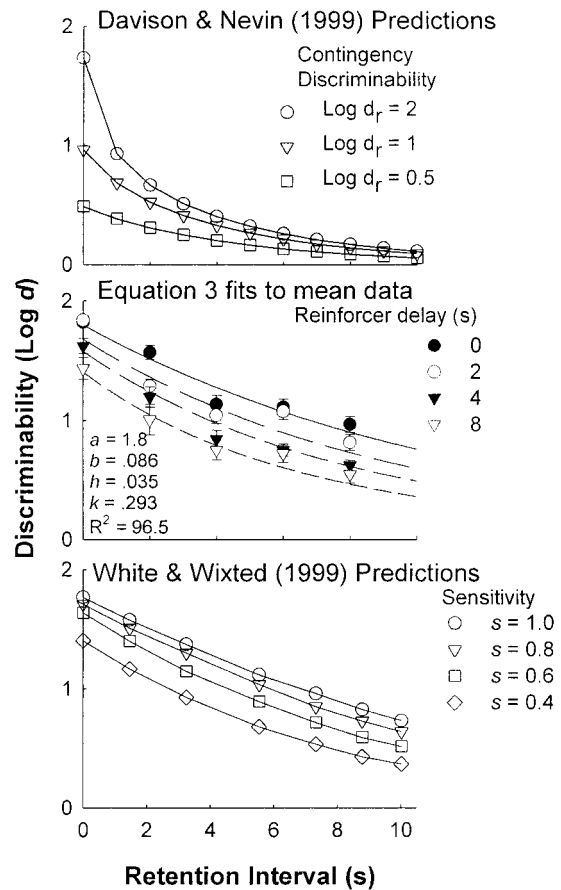


Fig. 6. Discriminability ( $\log d$ ) predicted by the model of Davison and Nevin (1999) as a function of retention interval for three values of contingency discriminability ( $\log d_r$ ) (top panel);  $\log d$  values averaged over pigeons as a function of retention interval for reinforcer delays of 0, 2, 4, and 6 s from the present data (center panel: functions have been fit to the data in the center panel using Equation 3); and  $\log d$  predicted by the White and Wixted (1999) model for three values of the reinforcer sensitivity ( $s$ ) (bottom panel).

inforcer delays of 0, 2, 4, and 8 s, and by fitting Equation 3 to these mean data. Note that the one set of parameter values given in Figure 6 applies to the functions for all of the reinforcer delays. The present data and their satisfactory description by Equation 3 therefore do not offer support for Davison and Nevin's application of their model to DMTS.

In Davison and Nevin's (1999) model, the reduction in discriminability with increasing reinforcer delay is attributed to a decrease in discriminability ( $d_r$ ) between response-reinforcer associations. In White and Wixted's

(1999) model, a reduction in discriminability results from decreased sensitivity when choice ratios are predicted by the ratio of reinforcers obtained by previous choices (Baum, 1974). McCarthy and Davison (1991) demonstrated that increasing the delay to reinforcement in DMTS decreased sensitivity of choice ratios to reinforcer ratios. As measured by the values of exponents ( $s$ ) of power functions, sensitivity values for individual pigeons ranged from  $s = 1.07$  to  $0.56$  at a 0-s delay and from  $s = 0.69$  to  $0.13$  at a 15-s delay. Mean sensitivity values in their study for 0-, 2-, and 15-s delays were 0.80, 0.79, and 0.56, respectively. They also reported a mean sensitivity of 0.26 for a 25-s delay, much longer than in the present study. Figure 6 (bottom panel) shows predictions from White and Wixted's model for sensitivity values of  $s = 1.0$ , 0.8, 0.6, and 0.4. Assuming that delaying the delivery of reinforcers generates decreased sensitivity, as demonstrated by McCarthy and Davison, Figure 6 (bottom panel) indicates that the increase in rate of forgetting with increasing reinforcer delay found in the present study can be predicted by White and Wixted's model. The predictions were generated by running simulations of the model with the parameter ( $D$ ) describing the distance between distributions of stimulus effect on the stimulus value dimension set at  $D = 5$  (see White & Wixted). Standard deviations of the distributions were assumed to increase as a simple exponential function of retention interval ( $t$ ),  $SD = \exp(8 \cdot t)$ , following White (2002a). When exponential functions were fitted to the predictions in Figure 6 (bottom panel), rate of forgetting increased with decreasing values of the exponent (with 100% variance accounted for in each case). Specifically, for sensitivity values of 1.0, 0.8, 0.6, and 0.4, the slope values were 0.086, 0.096, 0.114, and 0.133, respectively. The predicted levels of discriminability and changes in slope are in the range of those for the present data. More generally, this analysis supports the conclusion that the interaction between retention interval and reinforcer delay in the present experiment can be understood in terms of the discrimination made at the time the choice response is required. Descriptively, Equation 3 attributes the increase in slope of the forgetting functions with increasing reinforcer delay to an amplification of the effect of reinforcer delay

by long retention intervals. In other words, the interaction is the result of reduced discrimination between choice alternatives when reinforcers are delayed. In terms of White and Wixted's model, this reduced discrimination results from reduced reinforcer sensitivity. As emphasized in the treatment of remembering as discrimination (White, 2002a, 2002b), the discrimination is therefore conjointly influenced by factors related to both sample and choice stimuli.

## REFERENCES

- Baum, W. M. (1974). On two types of deviation from the matching law: Bias and undermatching. *Journal of the Experimental Analysis of Behavior*, 22, 231-242.
- Chung, S. H. (1965). Effects of delayed reinforcement in a concurrent situation. *Journal of the Experimental Analysis of Behavior*, 8, 439-444.
- Chung, S. H., & Herrnstein, R. J. (1967). Choice and delay of reinforcement. *Journal of the Experimental Analysis of Behavior*, 10, 67-74.
- D'Amato, M. R., & Cox, J. K. (1976). Delay of consequences and short-term memory in monkeys. In D. L. Medin, W. A. Roberts, & R. T. Davis (Eds.), *Processes of animal memory* (pp. 49-78). Mahwah, NJ: Erlbaum.
- Davison, M. C., & Nevin, J. A. (1999). Stimuli, reinforcers, and behavior: An integration. *Journal of the Experimental Analysis of Behavior*, 71, 439-482.
- Davison, M. C., & Tustin, R. D. (1978). The relation between the generalized matching law and signal-detection theory. *Journal of the Experimental Analysis of Behavior*, 29, 331-336.
- Edhouse, W. V., & White, K. G. (1988). Sources of proactive interference in animal memory. *Journal of Experimental Psychology: Animal Behavior Processes*, 14, 56-71.
- Ferguson, G. A. (1965). *Nonparametric trend analysis*. Montreal: McGill University Press.
- Foster, T. M., Temple, W., MacKenzie, C., DeMello, L. R., & Poling, A. (1995). Delayed matching-to-sample performance of hens: Effects of sample duration and response requirement during the sample. *Journal of the Experimental Analysis of Behavior*, 64, 19-31.
- Harper, D. N., & White, K. G. (1997). Retroactive interference and rate of forgetting in delayed matching-to-sample performance. *Animal Learning & Behavior*, 25, 158-164.
- Jones, B. M., White, K. G., & Alsop, B. (1995). On two effects of signalling the consequences for remembering. *Animal Learning & Behavior*, 23, 256-272.
- Luce, R. D. (1963). Detection and recognition. In R. D. Luce, R. R. Bush, & E. Galanter (Eds.), *Handbook of mathematical psychology* (Vol. 1, pp. 103-189). New York: Wiley.
- Marquardt, D. W. (1963). An algorithm for least-squares estimates of parameters. *Journal of the Society of Industrial and Applied Mathematics*, 11, 431-441.
- Mazur, J. E. (2001). Hyperbolic value addition and general models of choice. *Psychological Review*, 108, 96-112.

- McCarthy, D., & Davison, M. (1986). Delayed reinforcement and delayed choice in symbolic matching to sample: Effects on stimulus discriminability. *Journal of the Experimental Analysis of Behavior*, 46, 293–303.
- McCarthy, D., & Davison, M. (1991). The interaction between stimulus and reinforcer control on remembering. *Journal of the Experimental Analysis of Behavior*, 56, 51–66.
- McCarthy, D., & Voss, P. (1995). Delayed matching-to-sample performance: Effects of relative reinforcer frequency and of signaled versus unsignaled magnitudes. *Journal of the Experimental Analysis of Behavior*, 63, 33–52.
- McCarthy, D., & White, K. G. (1987). Behavioral models of delayed detection and their application to memory. In M. L. Commons, J. Mazur, J. A. Nevin, & H. C. Rachlin (Eds.), *Quantitative Analysis of Behavior: Vol. 5. The effect of delay and intervening events on reinforcement value* (pp. 29–54). New York: Erlbaum.
- Nevin, J. A., & Grosch, J. (1990). Effects of signaled reinforcer magnitude on delayed matching-to-sample performance. *Journal of Experimental Psychology: Animal Behavior Processes*, 16, 298–305.
- Renner, K. E. (1964). Delay of reinforcement: A historical review. *Psychological Bulletin*, 61, 341–361.
- Roberts, W. A. (1972). Short-term memory in the pigeon: Effects of repetition and spacing. *Journal of Experimental Psychology*, 94, 74–83.
- Rubin, D. C., & Wenzel, A. E. (1996). One hundred years of forgetting: A quantitative description of retention. *Psychological Review*, 103, 734–760.
- Sargisson, R. J., & White, K. G. (2001). Generalization of delayed matching to sample following training at different delays. *Journal of the Experimental Analysis of Behavior*, 75, 1–14.
- Weavers, R., Foster, T. M., & Temple, W. (1998). Reinforcer efficacy in a delayed matching-to-sample task. *Journal of the Experimental Analysis of Behavior*, 69, 77–85.
- White, K. G. (1985). Characteristics of forgetting functions in delayed matching to sample. *Journal of the Experimental Analysis of Behavior*, 44, 15–34.
- White, K. G. (1991). Psychophysics of direct remembering. In M. L. Commons, J. A. Nevin, & M. C. Davison (Eds.), *Signal detection: Mechanisms, models and applications* (pp. 221–237). Mahwah, NJ: Erlbaum.
- White, K. G. (2001). Forgetting functions. *Animal Learning & Behavior*, 29, 193–207.
- White, K. G. (2002a). Temporal generalization and diffusion in forgetting. *Behavioural Processes*, 57, 121–129.
- White, K. G. (2002b). Psychophysics of remembering: The discrimination hypothesis. *Current Directions in Psychological Science*, 11, 141–145.
- White, K. G., & McKenzie, J. (1982). Delayed stimulus control: Recall for single and relational stimuli. *Journal of the Experimental Analysis of Behavior*, 38, 305–312.
- White, K. G., & Wixted, J. T. (1999). Psychophysics of remembering. *Journal of the Experimental Analysis of Behavior*, 71, 91–113.
- White, K. G., & Wixted, J. T. (2001). Psychophysics of remembering. *The General Psychologist*, 36, 56–63.
- Wilkie, D. M., & Spetch, M. L. (1978). The effect of sample and comparison ratio schedules on delayed matching to sample in the pigeon. *Animal Learning & Behavior*, 6, 273–278.
- Williams, B. A. (1998). Relative time and delay of reinforcement. *Learning and Motivation*, 29, 236–248.
- Wixted, J. T. (1989). Nonhuman short-term memory: A quantitative reanalysis of selected findings. *Journal of the Experimental Analysis of Behavior*, 52, 409–426.
- Wixted, J. T., & Ebbesen, E. B. (1991). On the form of forgetting. *Psychological Science*, 6, 409–415.

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## APPENDIX A

Choice responses—correct red (CR), correct green (CG), error red (ER), and error green (EG)—made by each pigeon following each retention interval for each reinforcer delay, shown in order of condition for each pigeon.

Pigeon	Reinforcer delay (s)	Retention interval (s)											
		0				2				4			
		CR	CG	ER	EG	CR	CG	ER	EG	CR	CG	ER	EG
T2	0	32	36	0	0	37	33	0	0	32	35	0	0
	2	40	40	0	0	37	28	3	12	28	32	12	8
	4	37	40	3	3	28	39	12	1	25	32	15	8
	6	34	40	6	0	30	37	10	3	24	32	16	8
	8	34	34	1	3	28	29	12	10	22	28	18	10
	0	40	37	0	2	36	37	4	3	33	33	7	7
	1	40	40	0	0	36	40	4	0	34	37	6	3
	2	40	40	0	0	38	39	2	1	38	37	2	3
	0	40	39	0	1	36	38	4	2	35	34	5	6
	1	39	40	1	0	39	38	1	2	38	37	2	3
	2	40	40	0	0	38	37	2	3	35	35	5	5
	0	40	40	0	0	38	34	2	6	30	37	10	3
	2	39	40	1	0	39	38	1	2	33	37	7	3
	4	40	38	0	2	40	40	0	0	35	40	5	0
	6	37	38	3	2	33	32	7	8	29	35	11	5
	8	40	39	0	1	37	34	3	6	37	35	3	5
T3	0	40	40	0	0	40	40	0	0	39	40	1	0
	2	40	40	0	0	38	39	2	1	37	32	3	8
	4	38	39	0	0	39	38	1	0	38	38	0	1
	6	34	35	0	0	36	33	3	1	24	33	11	3
	8	32	40	0	0	42	36	1	0	28	40	7	0
	0	40	40	0	0	40	40	0	0	38	40	2	0
	1	40	40	0	0	40	40	0	0	38	39	2	1
	2	40	40	0	0	38	40	2	0	40	40	0	0
	0	40	40	0	0	39	40	1	0	40	40	0	0
	1	40	40	0	0	40	40	0	0	39	40	1	0
	2	40	40	0	0	40	39	0	1	40	38	0	2
	0	40	40	0	0	40	40	0	0	39	39	1	1
	2	40	40	0	0	40	40	0	0	40	40	0	0
	4	37	39	0	0	39	38	0	0	38	36	0	3
	6	40	40	0	0	39	40	1	0	35	40	5	0
	8	36	38	0	0	39	38	1	0	35	35	4	3
T4	0	40	39	0	1	36	39	4	1	37	37	3	3
	2	40	40	0	0	37	38	3	2	32	35	8	5
	4	40	39	0	1	37	39	3	1	37	31	3	9
	6	38	39	2	1	37	37	3	3	34	32	6	8
	8	31	35	7	5	22	39	18	11	21	28	19	12
	0	39	40	1	0	38	39	2	1	39	38	1	2
	1	40	40	0	0	37	33	3	7	33	31	7	9
	2	40	40	0	0	38	38	2	2	37	36	3	4
	0	40	40	0	0	39	40	1	0	38	34	2	6
	1	40	40	0	0	39	40	1	0	37	37	3	3
	2	40	40	0	0	39	36	1	4	35	36	5	4
	0	39	40	1	0	39	39	1	1	38	34	2	6
	2	40	40	0	0	35	37	5	3	35	36	5	4
	4	40	39	0	1	39	39	1	1	36	34	4	6
	6	40	39	0	1	38	33	2	7	37	37	3	3
	8	38	38	1	2	39	40	1	0	37	36	3	4
P1	0	40	40	0	0	40	40	0	0	40	40	0	0
	8	40	34	0	6	40	29	0	11	40	25	0	15
	6	40	39	0	1	38	37	2	3	36	34	4	6
	4	40	39	0	1	39	40	1	0	33	37	7	3
	2	40	40	0	0	36	38	4	2	39	39	1	1
	0	40	40	0	0	40	39	0	1	39	39	1	1
	2	39	38	1	2	38	39	2	1	38	35	2	5
	1	40	40	0	0	40	39	0	1	40	40	0	0

## APPENDIX A

(Extended)

Retention interval (s)							
6				8			
CR	CG	ER	EG	CR	CG	ER	EG
33	32	1	0	36	33	0	1
28	26	12	14	24	26	16	14
26	36	14	4	21	36	19	4
25	35	15	5	18	34	22	6
23	32	12	8	23	28	16	12
36	29	4	11	34	29	6	11
32	35	8	5	32	32	8	8
39	37	1	3	29	36	11	4
33	39	7	1	36	36	4	4
37	32	3	8	35	35	5	5
36	36	4	4	38	37	2	3
35	37	5	3	32	29	8	11
38	38	2	2	36	39	4	1
36	37	4	3	31	37	9	3
27	28	13	12	29	29	11	11
38	36	2	4	37	30	3	10
36	39	4	1	34	37	6	3
37	34	3	6	34	31	6	9
36	34	2	4	33	36	6	3
24	28	8	4	24	31	12	5
27	29	9	4	30	36	11	2
38	38	2	2	39	38	1	2
38	40	2	0	35	38	5	2
39	36	1	4	33	34	7	6
39	39	1	1	38	39	2	1
39	38	1	2	37	37	3	3
40	38	0	2	35	38	5	2
38	40	2	0	36	38	4	2
40	34	0	6	39	35	1	5
37	37	1	1	37	34	2	4
35	37	5	3	33	39	7	1
32	34	5	5	32	33	7	7
39	38	1	2	32	39	8	1
33	38	7	2	27	31	13	9
35	34	5	6	34	34	6	6
30	29	10	11	23	24	17	16
17	28	22	12	16	23	24	17
35	38	5	2	37	37	3	3
36	36	4	4	32	32	8	8
38	36	2	4	34	33	6	7
36	37	4	3	36	36	4	4
37	39	3	1	37	36	3	4
35	38	5	2	32	37	8	3
35	33	5	7	36	36	4	4
38	31	2	9	38	26	2	14
35	35	5	5	30	33	10	7
34	38	6	2	30	37	10	3
35	38	4	2	36	34	4	6
40	39	0	1	40	39	0	1
39	17	1	23	39	18	1	22
33	33	7	7	32	33	8	7
37	34	3	6	33	35	7	5
37	37	3	3	37	35	3	5
37	39	3	1	39	36	1	4
40	40	0	0	34	38	6	2
40	38	0	2	40	38	0	2



## APPENDIX A

(Continued)

Pigeon	Reinforcer delay (s)	Retention interval (s)											
		0				2				4			
		CR	CG	ER	EG	CR	CG	ER	EG	CR	CG	ER	EG
P2	0	40	40	0	0	39	40	1	0	37	40	3	0
	2	40	39	0	1	40	39	0	1	38	33	2	7
	1	40	40	0	0	38	40	2	0	40	40	0	0
	0	40	40	0	0	40	40	0	0	39	39	1	1
	8	40	38	0	2	38	36	2	4	37	35	3	5
	6	39	39	1	1	35	37	5	3	30	34	10	6
	4	39	39	0	0	39	34	1	5	39	34	1	5
	2	40	40	0	0	37	38	3	2	39	38	1	2
	0	40	40	0	0	40	40	0	0	36	37	4	3
	8	35	33	0	1	40	32	0	3	35	29	2	6
	6	33	34	0	0	37	29	1	5	33	31	0	3
	4	40	38	0	2	39	39	1	1	36	38	4	2
	2	40	40	0	0	37	40	3	0	34	40	6	0
	0	40	40	0	0	40	38	0	2	35	37	5	3
	2	40	40	0	0	37	40	3	0	35	34	5	6
P3	1	40	40	0	0	38	40	2	0	39	39	1	1
	0	40	40	0	0	39	39	1	1	36	38	4	2
	2	40	40	0	0	40	39	0	1	38	38	2	2
	1	40	40	0	0	39	40	1	0	35	39	5	1
	0	40	40	0	0	40	40	0	0	35	34	5	6
	8	35	34	0	1	38	32	2	4	33	31	4	4
	6	38	38	0	0	40	34	0	5	35	35	4	4
	4	40	40	0	0	36	36	4	4	35	34	5	6
	2	40	40	0	0	38	39	2	1	38	32	2	8
	0	39	40	1	0	39	40	1	0	35	37	5	3
	8	17	29	1	1	15	24	10	3	19	16	6	6
	6	10	15	0	4	11	12	3	5	11	6	4	7
	4	10	20	0	0	11	14	1	3	12	7	1	7
	2	41	43	0	0	41	38	7	4	35	36	8	8
	0	39	40	1	0	38	40	2	0	38	38	2	2
P4	2	40	40	0	0	37	40	3	0	36	37	4	3
	1	40	40	0	0	39	40	1	0	39	37	1	3
	0	40	40	0	0	40	38	0	2	37	37	3	3
	2	40	40	0	0	37	40	3	0	37	39	3	1
	1	40	40	0	0	38	39	2	1	37	34	3	6
	0	40	39	0	1	40	40	0	0	38	38	2	2
	8	37	40	0	0	40	38	4	2	29	38	11	2
	6	38	39	0	0	39	39	1	1	33	37	7	2
	4	40	40	0	0	40	37	0	3	33	35	7	5
	2	40	40	0	0	37	38	3	2	39	38	1	2
	0	40	39	0	1	40	39	0	1	35	31	5	9
	8	32	36	4	1	31	32	9	7	26	32	14	7
	6	40	38	0	2	37	25	3	15	29	28	11	12
	4	29	36	11	4	31	28	9	12	25	27	15	13
	2	38	36	2	4	31	36	9	4	29	34	11	6
	0	40	40	0	0	39	38	1	2	30	32	10	8
P4	2	40	40	0	0	39	40	1	0	35	36	5	4
	1	40	40	0	0	38	39	2	1	37	37	3	3
	0	40	40	0	0	37	40	3	0	34	35	6	5
	2	40	40	0	0	38	37	2	3	39	36	1	4
	1	40	40	0	0	38	35	2	5	33	34	7	6
	0	40	40	0	0	38	38	2	2	33	36	7	4
	8	31	36	2	1	32	32	6	4	26	31	10	5
	6	35	37	0	1	37	37	3	3	34	34	6	4
	4	38	39	2	1	37	37	3	3	34	34	6	6
	2	40	40	0	0	38	39	2	1	38	34	2	6

## APPENDIX A

(Continued, Extended)

Retention interval (s)							
6				8			
CR	CG	ER	EG	CR	CG	ER	EG
39	39	1	1	39	38	1	2
40	34	0	6	40	35	0	5
40	40	0	0	40	38	0	2
40	39	0	1	40	39	0	1
39	29	1	11	32	31	8	9
31	30	9	10	30	28	10	12
33	37	6	3	33	31	6	9
40	39	0	1	39	40	1	0
35	40	5	0	34	35	6	5
35	28	0	10	33	32	3	7
33	23	1	9	33	25	2	11
32	33	8	7	35	29	5	11
35	36	5	4	34	34	6	6
35	30	5	10	34	32	6	8
36	34	4	6	36	35	4	5
39	40	1	0	36	38	4	2
38	39	2	1	37	38	3	2
38	37	2	3	38	36	2	4
37	40	3	0	37	36	3	4
38	40	2	0	36	39	4	1
33	33	2	5	33	34	3	6
35	36	6	3	35	32	4	8
38	30	2	10	34	32	6	8
35	35	5	5	35	30	5	10
29	36	11	4	32	38	8	2
19	16	9	2	13	16	15	7
13	6	4	4	11	6	6	8
12	7	4	2	12	13	7	2
37	34	3	8	34	29	11	14
36	39	4	1	36	39	4	1
36	39	4	1	30	34	10	6
39	39	1	1	35	31	5	9
38	39	2	1	34	36	6	4
39	37	1	3	32	38	8	2
37	34	3	6	35	37	5	3
36	39	4	1	33	32	7	8
31	31	8	5	29	36	12	5
33	38	5	2	28	35	12	5
36	34	4	6	31	36	9	4
40	39	0	1	39	40	1	0
32	31	8	9	30	27	10	13
23	35	13	5	24	30	15	10
28	20	12	22	31	21	9	19
28	25	12	15	25	24	15	16
26	32	14	8	25	29	15	11
35	30	5	10	25	35	15	5
39	35	1	5	31	32	9	8
34	35	6	5	30	36	10	4
30	35	10	5	28	35	12	5
37	37	3	3	30	33	10	7
30	31	10	9	33	30	7	10
29	35	11	5	26	29	14	11
31	29	6	7	30	27	8	10
26	28	10	12	29	33	11	7
31	37	9	3	25	31	15	9
32	37	8	3	30	34	10	6

APPENDIX B  
Correct red (CR), correct green (CG), error red (ER), and error green (EG) responses from the last five sessions conducted in a condition using the Weavers et al. (1998) procedure for each pigeon.

Retention interval (s)	Pigeon T3				Pigeon T4				Pigeon P1				Pigeon P2				Pigeon P3				Pigeon P4			
	CR	CG	ER	EG	CR	CG	ER	EG	CR	CG	ER	EG	CR	CG	ER	EG	CR	CG	ER	EG	CR	CG	ER	EG
0	39	39	1	1	39	39	1	1	39	40	1	0	39	38	1	2	39	39	1	1	33	36	7	4
2	37	40	3	0	37	40	3	0	37	40	3	0	38	40	2	0	39	40	1	0	37	38	3	2
4	38	39	2	1	38	39	2	1	38	39	2	1	37	40	3	0	35	39	5	1	36	36	4	4
6	38	38	2	2	38	38	2	2	36	40	4	0	32	39	8	1	36	36	4	4	33	31	7	9
8	38	39	2	1	38	39	2	1	35	36	5	4	25	36	15	4	32	38	8	2	24	35	16	5